The lowest-order short-distance contribution to the $B_s \to \gamma\gamma$ decay

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Abstract: The complete calculation of the lowest order short-distance contributions to the $B_s \to \gamma\gamma$ decay in the SM are presented. The amplitude and branching ratio are calculated.

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The theoretical and experimental investigations of rare B-meson's decays provide precise test of the Standard Model (SM) and possible new physics beyond. Among the rare B decasys with particularly clean experimental signature is B_s-meson two photon radiative decay $B_s \rightarrow \gamma\gamma$. The present experimental bound on this decay is [1]

$$Br(B_s \rightarrow \gamma\gamma) \; < \; 1.48 \cdot 10^{-4} \tag{1}$$

B-meson double radiative decay has rich final state. Two photon can be in a CP-odd and CP-even state. Tferefore this decay allows us to study CP violating effects. In the SM the branching ratio of $B_s \rightarrow \gamma\gamma$ decay is of order10^{-7} without QCD corrections [2-5]. The branching ratio of this decay is enhanced with the addition of the QCD corrections [6-14]. The QCD corrections may correct the lowest order short-distance contributions to the $B_s \rightarrow \gamma\gamma$ decay in order of magnitude[2].

The planed experiments at the upcoming SLAC and KEK B-factories and hadronic accelerators are capable to measure the branching ratio as low as 10^{-8}. Therefore one expects the double radiative decay of the B_s-meson $B_s \rightarrow \gamma\gamma$ to be seen in these future facilities, thus stimulate theoretical investigations.

This decay is sensitive to possible new physics beyond the SM. Interstingly, the branching ratio can be enhanced in extensions of the SM [15,16]. Before one goes on to study other new physics which potentially can influence this decay, it stands to reasons to improve upon previous calculations [2-5].

In this paper we study the lowest-order short-distance contributions to the $B_s \rightarrow \gamma\gamma$ decay in the SM without QCD corrections. We do not neglect mass of s-quark. It is not immediately obvious how such investigation correct the branching ratio. The diagrams contributing to this decay are presented in Fig.1. The lowest-order short-distance contribution to the $B_s \rightarrow \gamma\gamma$ decay arise from the following set of graphs: i) triangle diagrams

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[2]In the paper [11] the authors have estimated the long-distance contributions to the $B_s \rightarrow \gamma\gamma$ decay arising from charmed-meson intermediate states. They have obtained that contributions of the diagrams with D_s^* may enhance the branching ratio more than an order of magnitude. The authors have mentioned that they neglected quite a few possible contributions to the process. They hope that the detail investigation does not invalidate the results presented in the paper [11].

with external photon leg (one particle reducible (OPR) diagrams), ii) box diagrams (one particle irreducible (OPI) diagrams).

One can write doun the amplitude for the decay $B_s \to \gamma\gamma$ in the following form, which is correct after gauge fixing for final photons

$$T(B_s \to \gamma\gamma) = \epsilon_1^\mu(k_1)\epsilon_2^\nu(k_2)[Ag_{\mu\nu} + iB\epsilon_{\mu\nu\alpha\beta}k_1^\alpha k_2^\beta] \tag{2}$$

where $\epsilon_1^\mu(k_1)$ and $\epsilon_2^\nu(k_2)$ are the polarization vectors of final photons with momenta k_1 and k_2 respectively. Let us fix photon polarization by the conditions

$$\epsilon_i \cdot \epsilon_j = 0, \qquad i,j = 1,2 \tag{3}$$

The conditions (3) with allowance for the energy-momentum conservation in the diagrams of Fig.1 yeld

$$\epsilon \cdot P = \epsilon \cdot p_b = \epsilon \cdot p_s = 0 \tag{4}$$

where

$$P = k_1 + k_2, \qquad p_b = p_s + k_1 + k_2 \tag{5}$$

Formulae (3)-(5) lead to useful kinematikal relation

$$k_1 \cdot k_2 = P \cdot k_i = \frac{1}{2}M_{B_s}^2, \qquad P \cdot p_b = m_b M_{B_s}, \qquad P \cdot p_s = -m_s M_{B_s}$$

$$p_b \cdot p_s = -m_s m_b, \qquad p_b \cdot k_i = \frac{1}{2}m_b M_{B_s}, \qquad p_s \cdot k_i = -\frac{1}{2}m_s M_{B_s} \tag{6}$$

With the aid of (3)-(6) one can calculate the cobntribution of each diagrams to the amplitude T. We used the 't Hooft-Feynman gauge and evaluated divergent Feynman integrals by means of dimensional regularization. Only OPR diagrams contain divergent parts. The divergent parts mutually cancel in the sum of amplitude and due to the GIM mechanism [17].

Using formula (2) we directly obtain the expression for the branching ratio

$$Br(B_s \to \gamma\gamma) = \frac{1}{32\pi M_{B_s}\Gamma_{tot}}[4 \mid A \mid^2 + \frac{1}{2}M_B^4 \mid B \mid^2] \tag{7}$$

As from Fig.1 is seen the correct procedure assumes the necessity of final photon rearangament. In the kinemastics (3)-96) this procedure leads to doubling of all contributions

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exept of diagrams 19 and 20, where both photons are emitted from the same space-time point:

$$A = A_{19} + A_{20} + 2\sum_{i=1}^{34}{}' A_i, \qquad B = B_{19} + B_{20} + 2\sum_{i=1}^{34}{}' B_i, \tag{8}$$

where the stress over the sum means absence in the sum of 19-th and 20-th terms.

The amplitude $T(B_s \rightarrow \gamma\gamma)$ and hence its CP-even and CP-odd parts can be written as a sum of contributions from up-quarks

$$T(B_s \rightarrow \gamma\gamma) = \sum_{i=u,c,t} \lambda_i T_i = \lambda_u T_u + \lambda_c T_c + \lambda_t T_t, \tag{9}$$

where $\lambda_i = V_{is}V_{ib}^*$ (V_{kl} being the corresponding elements of CKM matrix). Using the unitarity of the CKM matrix ($\sum \lambda_i = 0$) one can rewrite it in the form

$$T = \lambda_t \{T_t - T_c + \frac{\lambda_u}{\lambda_t}(T_u - T_c)\} \tag{10}$$

Below we restrict ourselves to evaluating the amplitude in the leading order $(1/M_W^2)$. The u-quark and c-quark contributions are equal in this approximation $(T_u = T_c)$. So, the expression for the amplitude becomes a simpler form

$$T = \lambda_t (T_t - T_c) \tag{11}$$

Only the OPR diagrams have nonzero contributions into amplitude A in this approximation. As conserning the amplitude B, it is grathered both from OPR diagrams and OPI diagrams 34 of Fig.1. The corresponding contributions are

$$A = i\frac{\sqrt{2}}{32\pi^2}G_F f_B (m_b - m_s) M_{B_s} \lambda_t \{(\frac{m_b}{m_s} + \frac{m_s}{m_b})[C(x_t) - C(x_c)] + C_1(x_t) - C_1(x_c)\}$$

$$B = i\frac{\sqrt{2}}{16\pi^2}G_F f_B \lambda_t \{(\frac{m_b}{m_s} + \frac{m_s}{m_b})[C(x_t) - C(x_c)] + C_2(x_t) - C_2(x_c) - 32M_{B_s}^2 I(m_c^2)\} \tag{12}$$

where

$$C(x) = \frac{22x^3 - 153x^2 + 159x - 46}{6(1-x)^3} + \frac{3(2-3x)x^2 \ell n x}{(1-x)^4}$$

$$C_1(x) = \frac{4}{3} \cdot \frac{6x^3 - 27x^2 + 25x - 9 + 6x^2 \ell n x}{(1-x)^3}$$

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$$C_2(x) = \frac{22x^3 - 12x^2 - 45x + 17}{3(1-x)^3} + \frac{2x(8x^2 - 15x + 4)\ell nx}{(1-x)^4}$$

$$I(m_c^2) = -\frac{1}{2M_{B_s}^2}\{1 + \frac{m_c^2}{M_{B_s}^2}(\ell n^2\frac{1+\beta}{1-\beta} - \pi^2 - 2i\pi\ell n\frac{1+\beta}{1-\beta})\}$$

$$x_t = \frac{m_t^2}{M_W^2}, \qquad \beta = \sqrt{1 - 4\frac{m_c^2}{M_{B_s}^2}} \tag{13}$$

We also used the following relations for hadronic matrix elements

$$< 0 \mid \bar{s}\gamma_\mu\gamma_5 b \mid B_s(P) >= -if_B P_\mu, \qquad < 0 \mid \bar{s}\gamma_5 b \mid B_s(P) >\approx if_B M_{B_s} \tag{14}$$

Using expressions (7),(12) and (13) one can estimate the branching ratio of the $B_s \rightarrow \gamma\gamma$ decay

$$Br(B_s \rightarrow \gamma\gamma) = 2 \cdot 10^{-7} \tag{15}$$

We have used the following set of parameters: $m_t = 175$ GeV, $m_b = 4.8$ GeV, $m_s = 0.5$ GeV, $f_B = 200$ MeV, $\lambda_t = 4 \cdot 10^{-2}$, $M_{B_s} = 5.3$ GeV, $\Gamma_{tot}(B_s) = 5 \cdot 10^{-4}$ eV. It should be mentioned that we do not neglect mass of s-quark. If one neglect mass of s-quark the branching ratio becomes 30% larger than the result (15). The upcoming B factories at SLAC, KEK and hadronic B projects at LHC, HERA, TEVATRON will be possible to study decay modes with branching ratio as small as 10^{-8}. Branching ratio 10^{-7} will be mesurable in these facilities. Detail investigation of the lowest-order short-distance contributions to the $B_s \rightarrow \gamma\gamma$ decay deckreases the branching ratio. This decay is sensitive to parameters and requierst further experimental and theoretical investigations.

Acknowledgments

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Figure

Fig.1. One particle reducible and one particle irreducible diagrams contributing to the $B_s \rightarrow \gamma\gamma$ decay.